

INTRODUCTION TO SMOOTH MANIFOLDS

HIDENORI SHINOHARA

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1. CHAPTER 1: SMOOTH MANIFOLDS

Exercise 1.1. Show that equivalent definitions of manifolds are obtained if instead of allowing U to be homeomorphic to *any* open subset of \mathbb{R}^n , we require it to be homeomorphic to an open ball in \mathbb{R}^n , or to \mathbb{R}^n itself.

Proof. It is clear that a “manifold” satisfying the open-ball or \mathbb{R}^n definition satisfies the open-subset definition. Let M be a manifold satisfying the open-subset definition. Let $x \in M$ be given and let U, \hat{U}, ϕ be given according to the definition. Since \hat{U} is open, there exists an open ball B such that $\phi(x) \in B \subset \hat{U}$. Restrict ϕ to $\phi^{-1}(B)$. Then $\phi^{-1}(B)$ is an open subset of M containing x , and $\phi|_{\phi^{-1}(B)}$ is a homeomorphism between $\phi^{-1}(B)$ and B . Thus M satisfies the open-ball definition.

$B(x, r) \subset \mathbb{R}^n$ is homeomorphic to \mathbb{R}^n by the map $(x_1 + a_1, \dots, x_n + a_n) \mapsto (\frac{a_1}{r-a_1}, \dots, \frac{a_n}{r-a_n})$ where $x = (x_1, \dots, x_n)$ is the center of $B(x, r)$ and r is the radius. Since the composition of two homeomorphisms gives a homeomorphism, M also satisfies the \mathbb{R}^n definition as well. \square

Exercise 1.6. Show that \mathbb{RP}^n is Hausdorff and second-countable, and is therefore a topological n -manifold.

Proof. From the definition of π , it is easy to see that $\pi(B(x, r))$ is open in \mathbb{RP}^n where $x \in S^n$ and $0 < r < 1$.

Let $[x], [y] \in \mathbb{RP}^n$ be given. Without loss of generality, assume $x, y \in S^n$. Let $r = \min\{|x - y|, |x + y|, 1\}/2$. Then $U_x = \pi(B(x, r)), U_y = \pi(B(y, r))$ contain $[x], [y]$, respectively. $\pi^{-1}(U_x), \pi^{-1}(U_y)$ are both open in $\mathbb{R}^{n+1} \setminus \{0\}$ which can be seen easily by writing down exactly which points belong to them, so U_x, U_y are both open in \mathbb{RP}^n . Then $\pi^{-1}(U_x \cap U_y) = \pi^{-1}(U_x) \cap \pi^{-1}(U_y) = \emptyset$, so $U_x \cap U_y = \emptyset$. Therefore, \mathbb{RP}^n is Hausdorff.

Let $\mathcal{B} = \{\pi(B(x, 1/k)) \mid x \in \mathbb{Q}^{n+1} \cap S^n, k \in \{2, 3, 4, \dots\}\}$. Then \mathcal{B} is a countable collection of open sets whose union is \mathbb{RP}^n . Let $U \subset \mathbb{RP}^n$ be a nonempty open set. Let $[x] \in U$. Since π is a quotient map, $\pi^{-1}(U)$ is open. Moreover, $x \in \pi^{-1}(U)$. Without loss of generality, $x \in S^n$. Then $x \in B(x', 1/k) \subset \pi^{-1}(U)$ for some $B(x', 1/k) \in \mathcal{B}$. Then $[x] = \pi(x) \in \pi(B(x', 1/k)) \subset \pi(\pi^{-1}(U)) = U$. Therefore, \mathcal{B} is a countable basis of \mathbb{RP}^n . \square

Exercise 1.7. Show that \mathbb{RP}^n is compact.

Proof. $\pi(S^n) = \mathbb{RP}^n$ and S^n is compact because it is a closed, bounded subset of \mathbb{R}^{n+1} . (Heine-Borel) Moreover, the image of a compact set under a continuous map is compact. (See A.45(a)) Thus \mathbb{RP}^n is compact. \square

Exercise 1.14. Suppose \mathcal{X} is a locally finite collection of subsets of a topological space M .

- (a) The collection $\{\overline{X} : X \in \mathcal{X}\}$ is also locally finite.
- (b) $\overline{\bigcup_{X \in \mathcal{X}} X} = \bigcup_{X \in \mathcal{X}} \overline{X}$.

Proof.

- (a) Let $p \in M$. Then there exists an open set U containing x such that there are only finitely many $X \in \mathcal{X}$ such that $U \cap X \neq \emptyset$. Let $X \in \mathcal{X}$.
 - If $U \cap X \neq \emptyset$, then $U \cap \overline{X} \supset U \cap X \neq \emptyset$.
 - If $U \cap X = \emptyset$, then U^c is closed, so $\overline{X} \subset U^c$. In other words, $U \cap \overline{X} = \emptyset$.

This shows that the number of $X \in \mathcal{X}$ that intersects U and the number of $\overline{X} \in \mathcal{X}$ that intersects U are the same. Therefore, $\{\overline{X} : X \in \mathcal{X}\}$ is also locally finite.

- (b) Since the closure of a set is defined to be the intersection of all closed sets containing it, $\bigcup_{X \in \mathcal{X}} \overline{X} \subset \overline{\bigcup_{X \in \mathcal{X}} X}$. Let $x \notin \bigcup_{X \in \mathcal{X}} \overline{X}$. Then there exists a neighborhood U of x such that U intersects only finitely many $X \in \mathcal{X}$. Let X_1, \dots, X_n denote them. By the same argument as part (a), $\overline{X_1}, \dots, \overline{X_n}$ are the only elements in $\{\overline{X} : X \in \mathcal{X}\}$ that U intersects. Since $x \notin \overline{X_i}$ for each $i = 1, \dots, n$, $U^c \cup \overline{X_1} \cup \dots \cup \overline{X_n}$ is a closed set which contains all $X \in \mathcal{X}$ but does not contain x . In other words, $x \notin \overline{\bigcup_{X \in \mathcal{X}} X}$.

□

Exercise 1.18. Let M be a topological manifold. Two smooth atlases for M determine the same smooth structure if and only if their union is a smooth atlas.

Proof. Let $\mathcal{A}, \mathcal{A}'$ be two smooth atlases.

Suppose that they determine the same smooth structure \mathcal{B} . Then $\mathcal{A} \cup \mathcal{A}' \subset \mathcal{B}$, so $\mathcal{A} \cup \mathcal{A}'$ must be a smooth atlas. By Proposition 1.17(a), $\mathcal{A} \cup \mathcal{A}'$ determines a unique smooth structure, but it must be \mathcal{B} because \mathcal{B} contains the union.

On the other hand, suppose that their union is a smooth atlas. Let \mathcal{B} be the smooth structure that the union determines. Such \mathcal{B} must exist by Proposition 1.17(a). By the same proposition, $\mathcal{A}, \mathcal{A}'$ must determine the unique smooth structures. However, they must be \mathcal{B} because \mathcal{B} contains both \mathcal{A} and \mathcal{A}' . □

Exercise 1.20. Every smooth manifold has a countable basis of regular coordinate balls.

Proof. Let M be an n -dimensional smooth manifold. We consider the special case that there exists a single chart (ϕ, U) with $U = M$. Let $x \in \hat{U}$ with rational coordinates. Then there exists $s > 0$ such that $B(x, s) \subset \hat{U}$. For each rational number $r \in (0, s)$, we consider the chart $(p \mapsto \phi(p) - x, \phi^{-1}(B(x, r)))$.

Let \mathcal{B} be the collection of all such charts for each $x \in \hat{U}$ and r . We claim that \mathcal{B} is a smooth atlas.

- Let $p \in M$. Then $\phi(p) \in \hat{U}$. Since \hat{U} is open, $\phi(p) \in B(x, r) \subset \hat{U}$ for some x with rational coordinates and a positive rational number r . Then $p \in \phi^{-1}(B(x, r))$, so the union of coordinate domains covers M . In other words, \mathcal{B} is an atlas.
- Let $(p \mapsto \phi(p) - x, \phi^{-1}(B(x, r))), (p \mapsto \phi(p) - x', \phi^{-1}(B(x', r')))) \in \mathcal{B}$ be given. Suppose $\phi^{-1}(B(x, r)) \cap \phi^{-1}(B(x', r')) \neq \emptyset$. Let ψ, ψ' denote the coordinate maps. Then $\psi' \circ \psi^{-1}$ is a composition of ϕ, ϕ^{-1} and translation maps, so it is smooth.

Therefore, \mathcal{B} is a smooth atlas.

Since \mathcal{B} is a smooth atlas, there exists a smooth structure \mathcal{A} on M containing \mathcal{B} by Proposition 1.17(a). We claim that \mathcal{B} , a subset of the smooth structure \mathcal{A} , is a countable basis of regular coordinate balls.

- \mathcal{B} is a countable collection because $x \in \mathbb{Q}^n$ and $r \in \mathbb{Q}$.
- Let $(p \mapsto \phi(p) - x, \phi^{-1}(B(x, r))) \in \mathcal{B}$ be given. Then there exists a chart $(p \mapsto \phi(p) - x, \phi^{-1}(B(x, r'))))$ in \mathcal{B} with $r' > r$. Let $B = \phi^{-1}(B(x, r)), B' = \phi^{-1}(B(x, r'))$. Let ψ denote the map $p \mapsto \phi(p) - x$. Then $\psi(B) = B(0, r)$ and $\psi(B') = B(0, r')$, respectively. Moreover, $\psi(\overline{B}) = \overline{B(0, r)}$ because ψ is a homeomorphism.

Work on the case when there is no chart that covers the entire manifold.

□

Exercise 1.39. Let M be a topological n -manifold with boundary.

- (a) $\text{Int } M$ is an open subset of M and a topological n -manifold without boundary.
- (b) ∂M is a closed subset of M and a topological $(n - 1)$ -manifold without boundary.
- (c) M is a topological manifold if and only if $\partial M = \emptyset$.
- (d) If $n = 0$, then $\partial M = \emptyset$ and M is a 0-manifold.

Proof.

- (a) Let $x \in \text{Int } M$. Let (ϕ, U) be an interior chart for x . Then $x \in U \subset \text{Int } M$ because every point in U is in an interior chart (ϕ, U) . A subspace of M must be Hausdorff and second-countable by Proposition A.17(g, i), so $\text{Int } M$ is a second-countable, Hausdorff space in which every point has a neighborhood homeomorphic to an open subset in \mathbb{R}^n . Thus $\text{Int } M$ is an n -manifold without boundary.
- (b) Since $\partial M = M \setminus \text{Int } M$ and $\text{Int } M$ is open in M , ∂M is closed in M . Let $x \in \partial M$. Let (ϕ, U) be a boundary chart of x . If a point $y \in U$ gets mapped into $\text{Int } \mathbb{H}^n$, then it is certainly an interior point. Thus $\phi(U \cap \partial M) \subset \partial \mathbb{H}^n$. Then $\pi_{n-1} \circ \phi$ is a homeomorphism that maps $U \cap \partial M$ into an open subset of \mathbb{R}^{n-1} where $\pi_{n-1} : (x_1, \dots, x_n) \mapsto (x_1, \dots, x_{n-1})$.
- (c) If ∂M is empty, then $M = \text{Int } M$, so (a) implies that M is an n -dimensional manifold. If M is a topological manifold, every point is an interior point. Since a point cannot be both an interior point and a boundary point, ∂M is empty.
- (d) If $n = 0$, then $\partial \mathbb{H}^0 = \emptyset$. Thus, the condition that $\phi(U) \cap \partial \mathbb{H}^n \neq \emptyset$ can never be satisfied, so there cannot be any boundary point.

□

Exercise 1.44. Suppose M is a smooth n -manifold with boundary and U is an open subset of M . Prove the following statements:

- (a) U is a topological n -manifold with boundary, and the atlas consisting of all smooth charts (V, ϕ) for M such that $V \subset U$ defines a smooth structure on U . With this topology and smooth structure, U is called an **open submanifold with boundary**.
- (b) If $U \subset \text{Int } M$, then U is actually a smooth manifold (without boundary); in this case we call it an **open submanifold of M** .
- (c) $\text{Int } M$ is an open submanifold of M (without boundary).

Proof. Let \mathcal{T} denote the topology of M and \mathcal{A} denote the smooth structure of M .

- (a) The subspace topology on U is equivalent to $\mathcal{T}_U = \{V \in \mathcal{T} \mid V \subset U\}$ because U is open. By Proposition A.17(A.18(Proof of Proposition A.17)), U is Hausdorff and second-countable. For every point $p \in U$, there exists a $V \in \mathcal{T}$ with a homeomorphism $\phi : V \rightarrow \hat{V}$ where \hat{V} is an open subset of \mathbb{R}^n (or \mathbb{H}^n). Since $U \cap V$ is an open subset of V , ϕ restricted to $U \cap V$ is a homeomorphism between $U \cap V$ and $\phi(U \cap V)$, which is an open subset of \mathbb{R}^n (or \mathbb{H}^n). Therefore, U is a topological n -manifold with boundary.

Let $\mathcal{A}_U = \{(\phi, V) \in \mathcal{A} \mid V \subset U\}$. Then \mathcal{A}_U is clearly a collection of charts on U whose union covers U . Moreover, any two charts in \mathcal{A}_U are clearly smoothly compatible. Let (ϕ, V) be a chart on U that is smoothly compatible with every chart in \mathcal{A}_U . Let $(\psi, W) \in \mathcal{A}$. Then $(\psi_{W \cap U}, W \cap U)$ is a chart on M and it must be smoothly compatible with every chart in \mathcal{A} . Therefore, $(\psi_{W \cap U}, W \cap U) \in \mathcal{A}$, so it must belong to \mathcal{A}_U . This implies that (ϕ, V) and $(\psi_{W \cap U}, W \cap U)$ are smoothly compatible. Since $V \subset W \cap U$, this implies that (ϕ, V) and (ψ, W) are smoothly compatible.

Thus (ϕ, V) is smoothly compatible with every chart in \mathcal{A} , so $(\phi, V) \in \mathcal{A}$. This implies that (ϕ, V) is in \mathcal{A}_U , so \mathcal{A}_U is indeed a maximal smooth atlas.

(b) Finish this!

(c) Finish this!

□

2. CHAPTER 2: SMOOTH MAPS

Exercise 2.1. Let M be a smooth manifold with or without boundary. Show that pointwise multiplication turns $C^\infty(M)$ into a commutative ring and a commutative and associative algebra over \mathbb{R} .

Proof.

- The constant map $f(p) = 0$ is clearly in $C^\infty(M)$ and it is the additive identity.
- The constant map $f(p) = 1$ is clearly in $C^\infty(M)$ and it is the multiplicative identity.
- Let $f, g \in C^\infty(M)$. Let $p \in M$ and (ϕ, U) be a smooth chart for p . Then $f \circ \phi^{-1}$ and $g \circ \phi^{-1}$ are both smooth (Exercise 2.3), real-valued maps defined on an open subset of \mathbb{R}^n . Thus $f + g$ is in $C^\infty(M)$. Moreover, $f + g = g + f$ because addition in \mathbb{R} is commutative.
- Let $f, g, h \in C^\infty(M)$. Let $p \in M$ and (ϕ, U) be a smooth chart for p . Then $f \circ \phi^{-1}$ and $g \circ \phi^{-1}$ are both smooth (Exercise 2.3), real-valued maps defined on an open subset of \mathbb{R}^n . Therefore, fg is in $C^\infty(M)$. Moreover, $fg = gf$ and $(fg)h = f(gh)$ because multiplication in \mathbb{R} is commutative and associative.
- Let $c \in \mathbb{R}$, $f \in C^\infty(M)$. Then cf can be seen as fg where g is the constant function whose value is c . As shown above, $cf \in C^\infty(M)$.

□

Exercise 2.2. Let U be an open submanifold of \mathbb{R}^n with its standard smooth manifold structure. Show that a function $f : U \rightarrow \mathbb{R}^k$ is smooth in the sense just defined if and only if it is smooth in the sense of ordinary calculus. Do the same for an open submanifold with boundary in \mathbb{H}^n .

Proof. f is smooth in the sense just defined if and only if $f \circ \text{Id}^{-1}$ is smooth in the sense of ordinary calculus. Since $f \circ \text{Id}^{-1} = f$, $f \circ \text{Id}^{-1}$ is smooth in the sense of ordinary calculus if and only if f is smooth in the sense of ordinary calculus. □

Exercise 2.3. Let M be a smooth manifold with or without boundary, and suppose $f : M \rightarrow \mathbb{R}^k$ is a smooth function. Show that $f \circ \phi^{-1} : \phi(U) \rightarrow \mathbb{R}^k$ is smooth for every smooth chart (U, ϕ) for M .

Proof. Let $\phi(x) \in \phi(U)$. Since f is smooth, there exists (V, ψ) such that $f \circ \psi^{-1} : \psi(V) \rightarrow \mathbb{R}^k$ is smooth and $x \in V$. Let $W = U \cap V$. Then $f \circ \psi^{-1} : \psi(W) \rightarrow \mathbb{R}^k$ is smooth and $\psi \circ \phi^{-1} : \phi(W) \rightarrow \psi(W)$ is a diffeomorphism where $\phi(W)$ is a neighborhood of W . Then the restriction of $f \circ \psi^{-1}$ to $\phi(W)$ is identical to $(f \circ \psi^{-1}) \circ (\psi \circ \phi^{-1})$. Since the composition of a smooth function is smooth, $f \circ \psi^{-1}$ is smooth. □

Exercise 2.7(Prove Proposition 2.5). Suppose M and N are smooth manifolds with or without boundary, and $F : M \rightarrow N$ is a map. Then F is smooth if and only if either of the following conditions is satisfied:

- For every $p \in M$, there exist smooth charts (U, ϕ) containing p and (V, ψ) containing $F(p)$ such that $U \cap F^{-1}(V)$ is open in M and the composite map $\psi \circ F \circ \phi^{-1}$ is smooth from $\phi(U \cap F^{-1}(V))$ to $\psi(V)$.
- F is continuous and there exist smooth atlases $\{(U_\alpha, \phi_\alpha)\}$ and $\{(V_\beta, \psi_\beta)\}$ for M and N , respectively, such that for each α and β , $\psi_\beta \circ F \circ \phi_\alpha^{-1}$ is a smooth map from $\phi_\alpha(U_\alpha \cap F^{-1}(V_\beta))$ to $\psi_\beta(V_\beta)$.

Proof. Let \mathcal{A}_M and \mathcal{A}_N be smooth structures of M and N . Suppose F is smooth. By Proposition 2.4, F is continuous. For every $p \in M$ there exist coordinate charts (U_p, ϕ_p) containing p and (V_p, ψ_p) containing $F(p)$ such that $F(U_p) \subset V_p$ and $\psi_p \circ F \circ \phi_p^{-1}$ is smooth from $\phi_p(U_p)$ to $\psi_p(V_p)$. Then $\{(U_p, \phi_p) \mid p \in M\} \subset \mathcal{A}_M$ and $\mathcal{A}_N \setminus \{(V_p, \psi_p) \mid p \in M\} \subset \mathcal{A}_N$ are smooth atlases. Moreover, for every (U_p, ϕ_p) and (V_q, ψ_q) , $\psi_q \circ F \circ \phi_p^{-1}$ is a smooth map from $\phi_p(U_p \cap F^{-1}(V_q))$ to $\psi_q(V_q)$ because $\psi_q \circ F \circ \phi_p^{-1} = (\psi_q \circ \psi_p^{-1}) \circ (\psi_p \circ F \circ \phi_p^{-1})$ where $\psi_q \circ \psi_p^{-1}$ and $\psi_p \circ F \circ \phi_p^{-1}$ are smooth. Therefore, the definition implies (b).

(b) implies (a) because if F is continuous, $F^{-1}(V_\beta)$ is open in M for every β , so $U \cap F^{-1}(V)$ is open in M .

Finally, we show that (a) implies the definition. Suppose F satisfies (a). Let $p \in M$. Let $(U, \phi) \in \mathcal{A}_M$ and $(V, \psi) \in \mathcal{A}_N$ be smooth charts satisfying the properties described in (a). Let $U' = U \cap F^{-1}(V)$ and consider $(U', \phi|_{U'})$. Then $(U', \phi|_{U'}) \in \mathcal{A}_M$ because it must be smoothly compatible with any other smooth coordinate chart in \mathcal{A}_M . Moreover, $F(U') \subset V$ and $\psi \circ F \circ (\phi|_{U'})^{-1} : \phi(U') \rightarrow \psi(V)$ is smooth. Therefore, (a) implies the definition.

Hence, (a), (b) and the definition are all equivalent. □

Exercise 2.7(Proof of Proposition 2.6). Let M and N be smooth manifolds with or without boundary, and let $F : M \rightarrow N$ be a map.

- (a) If every point $p \in M$ has a neighborhood U such that the restriction $F|_U$ is smooth, then F is smooth.
- (b) Conversely, if F is smooth, then its restriction to every open subset is smooth.

Proof. Let $\mathcal{A}_M, \mathcal{A}_N$ be smooth structures of M, N , respectively.

- (a) Let $p \in M$. Let U be a neighborhood of p such that $F|_U$ is smooth. By 1.44, U is a smooth manifold with the induced smooth structure $\mathcal{A}_U = \{(V, \phi) \in \mathcal{A}_M \mid V \subset U\}$. Since $F|_U$ is smooth, there exist $(V, \phi) \in \mathcal{A}_U$ and $(W, \psi) \in \mathcal{A}_N$ such that:
 - $F|_U(V) \subset W$.
 - $\psi \circ F|_U \circ \phi^{-1} : \phi(V) \rightarrow \psi(W)$ is smooth.
 Since $V \subset U$, $F(V) \subset W$, $\psi \circ F \circ \phi^{-1} : \phi(V) \rightarrow \psi(W)$ is smooth, and $(V, \phi) \in \mathcal{A}$. Therefore, F is smooth.
- (b) Let $U \subset M$ be an open subset. By 1.44, U is a smooth manifold with the induced smooth structure $\mathcal{A}_U = \{(V, \phi) \in \mathcal{A}_M \mid V \subset U\}$. Let $p \in U$. Then $p \in F$, so there exist $(V, \phi) \in \mathcal{A}_M, (W, \psi) \in \mathcal{A}_N$ such that $F(V) \subset W$ and $\psi \circ F \circ \phi^{-1} : \phi(V) \rightarrow \psi(W)$ is smooth. Then $(V \cap U, \phi|_{V \cap U})$ is a chart that is smoothly compatible with every chart in \mathcal{A}_M . Therefore, $(V \cap U, \phi|_{V \cap U}) \in \mathcal{A}_M$. Moreover, $\phi|_{V \cap U}(V \cap U) \subset \phi(V) \subset W$ and $\psi \circ F \circ (\phi|_{V \cap U}(V \cap U))^{-1}$ is clearly smooth. Therefore, $F|_U$ is smooth. □

Exercise 2.11(Proof of Proposition 2.10). Let M, N and P be smooth manifolds with or without boundary.

- (a) Every constant map $c : M \rightarrow N$ is smooth.
- (b) The identity map of M is smooth.
- (c) If $U \subset M$ is an open submanifold with or without boundary, then the inclusion map $U \rightarrow M$ is smooth.

Proof. Let $\mathcal{A}_M, \mathcal{A}_N, \mathcal{A}_P$ be smooth structures of M, N, P , respectively.

- (a) F is clearly continuous. Moreover, for every $(U_\alpha, \phi_\alpha) \in \mathcal{A}_M, (V_\beta, \psi_\beta) \in \mathcal{A}_N$, $\psi_\beta \circ F \circ \phi_\alpha^{-1}$ is a constant map, so it is smooth. By 2.7(Proof of Proposition 2.6), F is smooth.
- (b) Let $p \in M$. Choose $(U, \phi) \in \mathcal{A}_M$ such that $p \in U$. Then $F(U) \subset U$ and $\phi \circ F \circ \phi^{-1} = \text{Id}_U$, so it is smooth. Therefore, F is smooth.
- (c) By 1.44, $\mathcal{A}_U = \{(V, \phi) \mid V \subset U\}$ is a smooth structure of U . Let $p \in U$. Then $p \in V$ for some $(V, \phi) \in \mathcal{A}_U$. Then $(V, \phi) \in \mathcal{A}_M$, trivially. Since $F(V) \subset V$ and $\phi \circ F \circ \phi^{-1}$ is simply the identity map on V , F is smooth. □

3. CHAPTER 3: TANGENT VECTORS

Exercise 3.5(Proof of Lemma 3.4). Suppose M is a smooth manifold with or without boundary, $p \in M, v \in T_p M$, and $f, g \in C^\infty(M)$.

- (a) If f is a constant function, then $vf = 0$.
- (b) If $f(p) = g(p) = 0$, then $v(fg) = 0$.

Proof.

- (a) Let h be the constant function that always takes the value 1. Then $f(p) = ch(p)$ for some $c \in \mathbb{R}$. Then $v(ff) = f(p)vf + f(p)vf$, so $c^2v(h) = c^2v(h) + c^2v(h)$. Therefore, $c^2v(h) = 0$, so $cv(h) = 0$. Since v is linear, this implies $0 = v(ch) = v(f)$, so $v(f) = 0$.
- (b) $v(fg) = f(p)vg + g(p)vf = 0 + 0 = 0$. □

Exercise 3.7(Proof of Proposition 3.6). Let M, N , and P be smooth manifolds with or without boundary, let $F : M \rightarrow N$ and $G : N \rightarrow P$ be smooth maps, and let $p \in M$.

- (a) $dF_p : T_p M \rightarrow T_{F(p)} N$ is linear.
- (b) $d(G \circ F)_p = dG_{F(p)} \circ dF_p : T_p M \rightarrow T_{G \circ F(p)} P$.
- (c) $d(\text{Id}_M)_p = \text{Id}_{T_p M} : T_p M \rightarrow T_p M$.

(d) If F is a diffeomorphism, then $dF_p : T_p M \rightarrow T_{F(p)} N$ is an isomorphism, and $(dF_p)^{-1} = d(F^{-1})_{F(p)}$.

Proof. (a) $\forall v, w \in T_p M, \forall c \in \mathbb{R}, \forall f \in C^\infty(N)$,

$$\begin{aligned} dF_p(cv + w)(f) &= (cv + w)(f \circ F) \\ &= (cv)(f \circ F) + w(f \circ F) \\ &= c(v(f \circ F)) + w(f \circ F) \\ &= c(dF_p(v)(f)) + dF_p(w)(f) \\ &= (cdF_p(v))(f) + dF_p(w)(f) \\ &= (cdF_p(v) + dF_p(w))(f). \end{aligned}$$

Therefore, $dF_p(cv + w) = cdF_p(v) + dF_p(w)$.

(b) $\forall v \in T_p M, f \in C^\infty(P)$,

$$\begin{aligned} d(G \circ F)_p(v)(f) &= v(f \circ (G \circ F)) \\ &= v((f \circ G) \circ F) \\ &= (dF_p(v))(f \circ G) \\ &= (dG_{F(p)}(dF_p(v)))(f) \\ &= ((dG_{F(p)} \circ dF_p)(v))(f) \end{aligned}$$

Therefore, $d(G \circ F)_p = dG_{F(p)} \circ dF_p$.

(c) $\forall v \in T_p(M), \forall f \in C^\infty(M)$,

$$\begin{aligned} d(\text{Id}_M)_p(v)(f) &= v(f \circ \text{Id}_M) \\ &= v(f). \end{aligned}$$

Therefore, $d(\text{Id}_M)_p(v) = v$, so $d(\text{Id}_M)_p = \text{Id}_{T_p M}$.

(d) □

4. APPENDIX A: REVIEW OF TOPOLOGY

Exercise A.18(Proof of Proposition A.17). Let X be a topological space and let S be a subspace of X .

- (a)
- (b)
- (c)
- (d)
- (e)
- (f) If \mathcal{B} is a basis for the topology of X , then $\mathcal{B}_S = \{B \cap S \mid B \in \mathcal{B}\}$ is a basis for the subspace topology on S .
- (g) If X is Hausdorff, then so is S .
- (h) If X is first-countable, then so is S .
- (i) If X is second-countable, then so is S .

Proof.

- (a)
- (b)
- (c)
- (d)
- (e)
- (f) The union of $B \cap S$ is S . Let $U \cap S$ be an open subset of S where U is open in X , and $x \in U \cap S$. Then there exists $B \in \mathcal{B}$ such that $x \in B \subset U$ since \mathcal{B} is a basis. Therefore, $x \in B \cap S \subset U \cap S$ with $B \cap S \in \mathcal{B}_S$.

- (g) Let $x \neq y \in S$. There exist two disjoint open sets U, V of X containing x, y , respectively. Then $U \cap S$ and $V \cap S$ are disjoint open sets of X containing x, y , respectively.
- (h)
- (i) Let \mathcal{B} be a countable basis of X . Then $\{B \cap S \mid B \in \mathcal{B}\}$ is a countable basis of S by (f).

□

5. APPENDIX C: REVIEW OF CALCULUS

Exercise C.1. Suppose that $F : U \rightarrow W$ is differentiable at $a \in U$. Show that the linear map satisfying

$$\lim_{v \rightarrow 0} \frac{|F(a+v) - F(a) - Lv|}{|v|} = 0$$

is unique.

Proof. Let L, L' be two such linear maps.

$$\begin{aligned} \lim_{v \rightarrow 0} \frac{|Lv - L'v|}{|v|} &= \lim_{v \rightarrow 0} \frac{|(F(a+v) - F(a) - L'v) - (F(a+v) - F(a) - Lv)|}{|v|} \\ &= \lim_{v \rightarrow 0} \frac{|F(a+v) - F(a) - Lv|}{|v|} + \lim_{v \rightarrow 0} \frac{|F(a+v) - F(a) - L'v|}{|v|} \\ &= 0 + 0 = 0. \end{aligned}$$

If $L \neq L'$, $(L - L')v_0 \neq 0$ for some v_0 . Then $\lim_{v \rightarrow 0} \frac{|Lv - L'v|}{|v|} = \lim_{h \rightarrow 0} \frac{|L(hv_0) - L'(hv_0)|}{|hv_0|} = \frac{|(L - L')v_0|}{|v_0|} \neq 0$. This is a contradiction, so $L = L'$. □

6. DICTIONARY

6.1. Topological Manifolds.

Definition 6.1 (Topological Manifold). A *topological n -manifold* is a Hausdorff, second-countable topological space each point of which has a neighborhood that is homeomorphic to an open subset \mathbb{R}^n .

Definition 6.2 (Coordinates). Let M be a topological n -manifold. Let U be an open subset of M , \hat{U} be an open subset of \mathbb{R}^n , $\phi : U \rightarrow \hat{U}$ be a homeomorphism.

- The pair (U, ϕ) is called a *coordinate chart* or a *chart*.
- U is called a *coordinate domain* or a *coordinate neighborhood* and ϕ is called a *coordinate map*.
- If $\phi(U)$ is an open ball in \mathbb{R}^n , U is called a *coordinate ball*.
- If $\phi(U)$ is an open cube in \mathbb{R}^n , U is called a *coordinate cube*.

Definition 6.3 (Atlas). Let M be a topological n -manifold. An *atlas for M* is a collection of charts (U_α, ϕ_α) such that $M = \bigcup_\alpha U_\alpha$.

Definition 6.4 (Transition Map). Let M be a topological n -manifold and $(U, \phi), (V, \psi)$ be coordinate charts such that $U \cap V \neq \emptyset$. $\psi \circ \phi^{-1} : \phi(U \cap V) \rightarrow \psi(U \cap V)$ is called a *transition map* from ϕ to ψ .

Definition 6.5 (Closed Upper Half-Space). $\mathbb{H}^n = \{(x^1, \dots, x^n) \in \mathbb{R}^n \mid x^n \geq 0\}$, and $\partial\mathbb{H}^n = \{(x^1, \dots, x^n) \in \mathbb{R}^n \mid x^n = 0\}$.

Definition 6.6 (Manifold With Boundary). Let M be a second-countable Hausdorff space and fix n . Suppose that for every $p \in M$, one of the following conditions is satisfied:

- (1) There exists a neighborhood U of p and a homeomorphism $\phi : U \rightarrow \hat{U}$ where \hat{U} is an open subset of \mathbb{R}^n . p is called an *interior point* and (U, ϕ) is called an *interior chart*.
- (2) There exists a neighborhood U of p and a homeomorphism $\phi : U \rightarrow \hat{U}$ where \hat{U} is an open subset of \mathbb{H}^n with $\hat{U} \cap \partial\mathbb{H}^n \neq \emptyset$. p is called a *boundary point* and (U, ϕ) is called a *boundary chart*.

Then M is called an *n -dimensional topological manifold with boundary*. Note that every topological manifold is a topological manifold with boundary.

6.2. Smooth Manifolds.

Definition 6.7 (Smoothly Compatible). Let M be a topological n -manifold. Two coordinate charts $(U, \phi), (V, \psi)$ are called *smoothly compatible* if $U \cap V = \emptyset$ or the transition map $\psi \circ \phi^{-1}$ is a diffeomorphism.

Definition 6.8 (Smooth Atlas). Let M be a topological n -manifold. A *smooth atlas* is an atlas \mathcal{A} such that any two charts in \mathcal{A} are smoothly compatible with each other.

Definition 6.9 (Smooth Structure). If M is a topological n -manifold, an atlas \mathcal{A} that is not properly contained in any larger smooth atlas is called *maximal* or a *smooth structure on M* .

Definition 6.10 (Smooth Manifold). A *smooth manifold* is a topological manifold equipped with a smooth structure.

Definition 6.11. Suppose (M, \mathcal{A}) is a smooth manifold.

- Any chart $(U, \phi) \in \mathcal{A}$ is called a *smooth chart*.
- Given a smooth chart (U, ϕ) , U is called a smooth coordinate domain and ϕ is called a *smooth coordinate map*.
- Given a smooth chart (U, ϕ) , U is called a *smooth coordinate ball* if it is a coordinate ball.

Remark 6.12. One must define a smooth structure on a topological manifold before talking about a smooth chart.

Definition 6.13 (Smooth Maps). Let M, N be smooth manifolds with or without boundary and $F : M \rightarrow N$ be a map. F is a *smooth map* if for every $p \in M$, there exist smooth charts (U, ϕ) containing p and (V, ψ) containing $F(p)$ such that

- $F(U) \subset V$;
- $\psi \circ F \circ \phi^{-1} : \phi(U) \rightarrow \psi(V)$ is smooth.

Definition 6.14 (Diffeomorphism). Let M, N be smooth manifolds with or without boundary. A diffeomorphism is a smooth map $F : M \rightarrow N$ with a smooth inverse.

6.3. Tangent Vectors.

Definition 6.15 (Derivation). Let M be a smooth manifold with or without boundary. A derivation at $p \in M$ is a linear map $v : C^\infty(M) \rightarrow \mathbb{R}$ such that

$$v(fg) = f(p)vg + g(p)vf$$

for all $f, g \in C^\infty(M)$.

Definition 6.16 (Tangent Space). The tangent space $T_p M$ to M at p is the vector space of all derivations of $C^\infty(M)$ at p .

Definition 6.17 (Differential). M, N are smooth manifolds with or without boundary, and $F : M \rightarrow N$ is a smooth map. The *differential of F at p* is the linear map $dF_p : T_p M \rightarrow T_{F(p)} N$ defined by

$$dF_p(v) := f \mapsto v(f \circ F)$$

Equivalently, $\forall v \in T_p M, \forall f \in C^\infty(N), dF_p(v)(f) = v(f \circ F)$.